Indian J. Phys. **70A** (3) 461–464 (1996)

IJP A
– an international journal

WHAT IS A PHENOMENON ?*

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Abstract: An example is given of a simple modification of the Mach-Zehnder interferometer that shows that no classical picture can be formed of a quantum mechanical entity (or "particle") until the measurement is completed.

Key Words : phenomenon, measurement, interpretation

PACS number : 03.65.Bz

Einstein was unhappy with the feature of quantum mechanics that makes what happens depend upon what the observer chooses to measure. He attempted to show that it is incompatible with the reasonable idea of reality that the universe exists "out there" independent of all acts of observation. In his attempt to make clear to Einstein his own point of view Bohr found himself compelled to introduce the word *"phenomenon"* . Wheeler [1] has proposed a "delayed choice" version of the double-slit experiment in an attempt to put Bohr's point of view more sharply. The essential point of this experiment is captured in a Mach-Zehnder interferometer with particles like photons or electrons incident on the first beam splitter S_1 one at a time. The wave function of the incident particle is split into two equal parts which are reflected by two mirrors A and B to a crossing point. Counters located past this point can tell by which path or route an arriving photon or electron has come. In the alternative arrangement a second beam splitter S_2 is inserted at the point of crossing. On one side it brings the two wave functions into destructive interference (dark port), so that the counter located on that side never registers any count. On the other side the wave functions are brought into constructive interference (bright port) so that the counter on that side registers all the particles. This counter gives evidence that the arriving particle came by both

* Late arrival

routes. In the delayed-choice version of the experiment one decides whether to insert the beam-splitter S_2 at the crossing point or to take it out at the very last picosecond, after the particle has accomplished its travel. Thus one decides whether the particle "shall have come by one route or by both routes" after it has "already accomplished its travel". In other words, one has no right to say what the particle is doing in *all its long course from point of entry to point of detection.* The phenomenon-to-be *"is not yet a phenomenon until it has been brought to a close by an irreversible act of amplification such as the blackening of a grain of silver bromide emulsion or the triggering of a photodetector"* [1].

In this short tribute to Haridas Banerjee on his sixtieth birthday, let me propose a variation of the delayed-choice experiment which raises considerable doubt about the *reasonableness* of the Bohr-Wheeler complementarity interpretation. Let us imagine that the incident particle *a* is an electrically charged fermion, and that a second charged fermion *b*, much lighter than *a*, is placed mid-way between the two possible paths of *a* between the "mirrors" A and B. With the second beam splitter S_2 inserted at the point of crossing, the wave function of *a* in the region between A and B is

$$\psi(a)=\frac{1}{\sqrt{2}}\,[\,\psi_1(a)+\psi_2(a)\,] \tag{1}$$

where $\psi_1(a)$ and $\psi_2(a)$ correspond to the two possible paths and are spatially non-overlapping. So, the current in this region is given by

$$\begin{aligned} j_\mu(a) &= \frac{1}{2}[\,\overline{\psi}_1(a)\gamma_\mu\psi_1(a)+\overline{\psi}_2(a)\gamma_\mu\psi_2(a)\,] \\ &\equiv j_\mu^{\,1}(a)+j_\mu^{\,2}(a)\,. \end{aligned} \tag{2}$$

Although the interference terms are missing, notice that the current is still a *coherent* sum of two terms. According to the principle of minimal coupling the interaction Hamiltonian *density* for the system *a-b* is then

$$\mathcal{H}_{int} = e\,(\,j_\mu(a)+j_\mu(b)\,)\,A^\mu \tag{3}$$

where A^μ is the electromagnetic potential and

$$j_\mu(b) = \overline{\psi}(b)\gamma_\mu\psi(b) \tag{4}$$

In the non-relativistic limit, the currents reduce to their usual Schrodinger forms and only the components $\mu=0$ survive. To the lowest order in the coupling e the matrix element for *a-b* scattering is therefore given by

$$m \propto e^2 \, \tilde{j}_\mu(a) \, D^{\mu\nu} \tilde{j}_\nu(b) \, , \tag{5}$$

where the tilde over j denotes its Fourier transform and $D^{\mu\nu}$ is the photon propagator in momentum space. However, with S_2 removed, the wave function of *a* collapses, and the state of *a* between A and B can no longer be described by a single wave function of the form (1). It is then an *incoherent mixture* of $\psi_1(a)$ and $\psi_2(a)$ ('which path" information being now available) described by a diagonal density matrix, and therefore the current is also an *incoherent mixture* of $j_\mu{}^1(a)$ and $j_\mu{}^2(a)$. Consequently, it might appear that the scattering cross-section should in this case be determined by

$$|m'|^2 \quad \left|\tilde{j}_\mu{}^1(a) D^{\mu\nu} \tilde{j}_\nu(b)\right|^2 + \left|\tilde{j}_\mu{}^2(a) D^{\mu\nu} \tilde{j}_\nu(b)\right|^2 \tag{6}$$

which is different from $|m|^2$ which contains interference terms and so does not yield "which path" information about *a*. Thus, the scattering behaviour of *b* would appear to be different in the two cases.

Actually, a little thought shows that this cannot be the case according to quantum mechanics. The reason is that collapse of the wave function occurs only *after* one of the detectors fires and the measurement is completed, *not before*. This can be tested in delayed-choice experiments by inserting S_2 at the crossing point at the very last moment. The fact that coherence is not lost until S_2 is inserted is revealed by the appearance of interference. If this were not true, one would be able to send superluminal signals. Consider a set-up where S_2 is in place at the crossing point and particles like *a* are incident on S_1 one at a time with a certain frequency. As soon as S_2 (which can be placed as far away from *b* as one likes) is withdrawn, *b* would start to behave differently. (Strictly speaking, there would be a small time lag due to the propagation of the light signal between *a* and *b*, but this can be made as small as one likes compared with the time taken by light to travel from S_2 to *b*.) That would constitute superluminal signaling.

This highlights the unreasonableness of the complementarity interpretation of *phenomena*. Although the particle *b* behaves in the same way irrespective of the delayed-choice made (S_2 in place or S_2 removed from the crossing point), the Bohr-Wheeler interpretation invokes mutually exclusive and complementary classical pictures of *a* in the two cases after completion of the measurement. Surely, the identical behaviour of the auxiliary particle *b* in the two cases indicates that there does exist a reality "out there" that is not influenced by what one chooses to observe. This is why the *causal* and *ontological* interpretation of de Broglie and Bohm [3] is preferable. In this interpretation the particle always has a definite hidden trajectory determined by the quantum potential which is itself determined by the wave function of the total system (particle + apparatus).

Acknowledgements

The author acknowledges critical and illuminating discussions with C.S.Unnikrishnan.

This work was done as part of a project funded by the Department of Science & Technology, Government of India.

References

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[2] D. Bohm, Phys. Rev. **85**, 166 and 180 (1952) (reprinted in Wheeler and Zurek (1983)).